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Challenges and Progress in Controlling Dynamics in Gas Turbine Combustors

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Combustion dynamics impact the design of both conventional diffusion flame gas turbine combustors and lean premixed combustion systems. The occurrence of dynamics in diffusion flame combustors can generally be eliminated through changes to the fueling system or operating characteristics driven primarily through empirical design know-how. Lean premixed combustors, such as industrial aeroderivative dry low-emissions combustors, have more persistent dynamics problems that are only partially ameliorated with application of empirical tools and controls. With continuing emphasis on reducing emissions and cost and increasing performance of turbo-propulsion engine combustors, the design direction of flight engines is approaching the lean premixed limit; thus, there is a need for improved tools and control strategies for combustion dynamics in these applications as well. The components of a combined analytical, experimental, and computational approach to understanding and controlling combustion dynamics are being developed. With successful implementation of such an analytical and control mechanism, further improvements in the emissions, stability, and durability characteristics of both flight and industrial combustors will become possible.

Introduction

THE appearance of combustion dynamics problems in aircraft propulsion and aeroderivative industrial engine combustors presents a great challenge for combustor designers. Dynamics are objectionable for several reasons. Under some conditions, the activity within the combustor can generate an externally audible tone at intolerable levels during engine operation. The pressure oscillation can also drive resonant vibratory behavior in mechanical components, leading to significant hardware damage.

A fundamental issue in designing gas turbine combustors is the late stage of the development process at which combustion dynamics phenomena become apparent. Many, if not most of the critical performance parameters of a combustor can be determined analytically or through a combination of analysis and component testing. Although some indications of the susceptibility of a combustion system to high levels of dynamics can sometimes be inferred from component tests, the behavior of the full system cannot be predicted on the basis of either analysis or component testing. The severity and character of the problem is not determined until an engine test is conducted, at which point significant changes to component design are very expensive and are likely to have major schedule and development cost impacts. Various acoustic control strategies, both passive and active, are then applied to deal with the unacceptable dynamics levels. However, the application of these strategies is a very empirical process with little assurance of success.

The conventional approach to this problem is based largely on empirical correlations and design experience. Attempts are made to predict frequencies and amplitudes of combustion acoustic waves, such that none of the subsystems (fuel nozzle, heat shield, combustor liners, etc.) of the total combustion system have natural frequencies that can couple with the combustion acoustic frequency. Although success has been obtained in predicted acoustic mode shapes and frequencies, the amplitude of the oscillation(s) is not easily predicted.

To reduce the level of risk posed by uncontrollable combustion acoustic behavior, detection and abatement of combustion acoustic susceptibility is required in the early stages of a design. A comprehensive strategy to predict, avoid, and/or improve the combustion acoustic performance of a combustion system includes both analytical and experimental determination of system and component properties and interactions. The basic framework of such a strategy is shown in Fig. 1. Briefly, a semi-analytical model is used to link the acoustic characteristics of the subcomponent parts of the combustion system and boundaries. The characteristics of these subcomponents can be derived either from analytical models or from well-characterized empirical testing. A more detailed description will be given in a later section.

The present work is intended to provide an overview of the combustion dynamics problems observed in aeroderivative industrial gas turbine engines and flight propulsion engines. The fundamental issues driving combustion dynamics in practical gas turbine combustors are reviewed as a means to interpret the observed combustion behavior. Several methods used in the laboratory and in production engines for controlling combustion dynamics are described, along with two examples of combustion dynamics control in production gas turbine engines. Finally, a framework for analysis and design of gas turbine combustors to mitigate the occurrence and impact of combustion dynamics is presented.

Fundamental Causes of Combustion Dynamics

The occurrence of combustion dynamics is generally understood as being dependent on a coupling between pressure oscillations and energy release rate, often referred to as the Rayleigh criterion. A pressure disturbance affects the local instantaneous heat release rate, which in turn creates a pressure disturbance with some time (or phase) lag to the initial disturbance. An acoustic cavity permits reflection of the pressure disturbance, thus, closing the feedback loop that causes excessive (and destructive) pressure oscillations. Two critical parameters in determining whether the overall feedback loop will be stable or unstable are the relative phase lag between the pressure and heat release oscillations and the amount of damping present.

The first category of coupling mechanisms is the pressure disturbance interaction with the instantaneous flame position and shape. As the flame surface responds to the pressure disturbance, its response can generate an acoustic wave of its own. These coupling mechanisms should be relatively insensitive to details in the fueling system and are often identified with high-frequency (>1 kHz)

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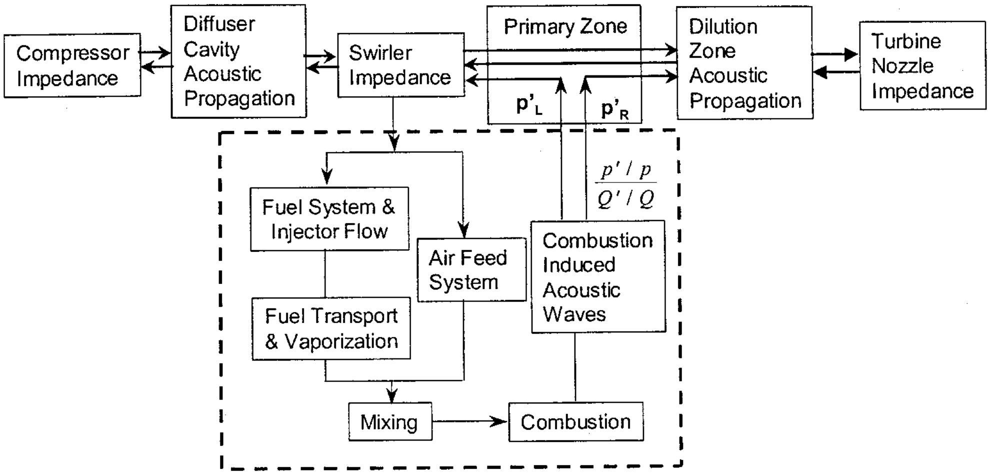


Fig. 1 Framework for combustion dynamics modeling.

acoustic activity. Lieuwen[1] gives an excellent review on the modeling processes of premixed combustion acoustic wave interaction. Based on analytical and experimental observations, it appears that the combustion process is increasingly sensitive to perturbation in equivalence ratio ϕ, under lean operating conditions.

The second category of coupling mechanisms is often termed fuel/air wave coupling. Within this category are several submechanisms, which share a common interaction between a pressure oscillation and the local fuel/air ratio of the combustor. The physical interaction can take place through effects upon local airflow rate, fuel flow rate, or fuel spray characteristics. This type of interaction is often identified with midrange frequencies (100–1000 Hz).

The third category is incipient blowout coupling. This mechanism is unusual in that it is an engine system-level coupling mechanism. An example is when a segment of a combustor locally reaches a low enough fuel/air ratio to extinguish. The energy reaching the turbine immediately reduces, causing the rotor speed to decrease. The airflow through the engine is reduced, causing the fuel/air ratio to increase and the blown-out segment to reignite. This is often detected as a very low-frequency mode (<30 Hz) and is not typically classified as a combustion acoustic phenomenon.

Control Strategies

Methods for controlling combustion dynamics in practical gas turbine combustors fall into three basic categories. Fundamental design changes to the fuel/air mixing device have been shown to demonstrate significant impacts on combustion dynamics behavior.[2,3] These changes can influence either or both the fuel flow and airflow paths[4] and are generally derived empirically though component and engine test.

Control of combustion dynamics can often be achieved through manipulation of the operating characteristics of the combustor. This can take the form of adjustments in radial staging of fuel flow (and thus flame temperature) distribution,[5] in axial fuel staging adjustments,[6] or in asymmetric fuel distribution.[7] Such fuel distribution strategies generally deteriorate the NO_X emissions performance of the combustor because they shift the flame temperatures away from the ideal uniform distribution.

Finally, combustion dynamics can be affected by the use of both passive and active control devices. The passive controls are typically Helmholtz resonators[8] or quarter-wave tubes[5] and serve to act as damping devices in the oscillating system. These devices have demonstrated successful suppression of acoustics in gas turbine combustors. A disadvantage of these devices is that they only operate over a limited frequency range, thus, requiring empirical selection of the number and configuration of the devices.

Active controls also take multiple forms, the most common being modulation of the fuel flow with a frequency and phase relationship designed to interact destructively with the combustion dynamic oscillation. This modulation can take the form of the main fuel flow,[9,10] or a smaller secondary fuel injection site,[11] possibly intended to act more directly on regions in which the Rayleigh index is largest (see Ref. 12). Whereas significant suppression of combustion dynamics has been demonstrated in several subscale laboratory combustors, several barriers to implementation in full-scale gas turbine combustors still exist. First, the geometry of an annular combustor is far more complex than that of a simple can-type laboratory combustor. The control algorithms for controlling the complex acoustic mode structures in an annular combustor still need to be developed and proven. Also, the reliability and durability of the sensors, actuators, and control systems need to be comparable to those of the gas turbine itself to avoid causing unscheduled maintenance events.

Rich-Dome Combustion Dynamics Example

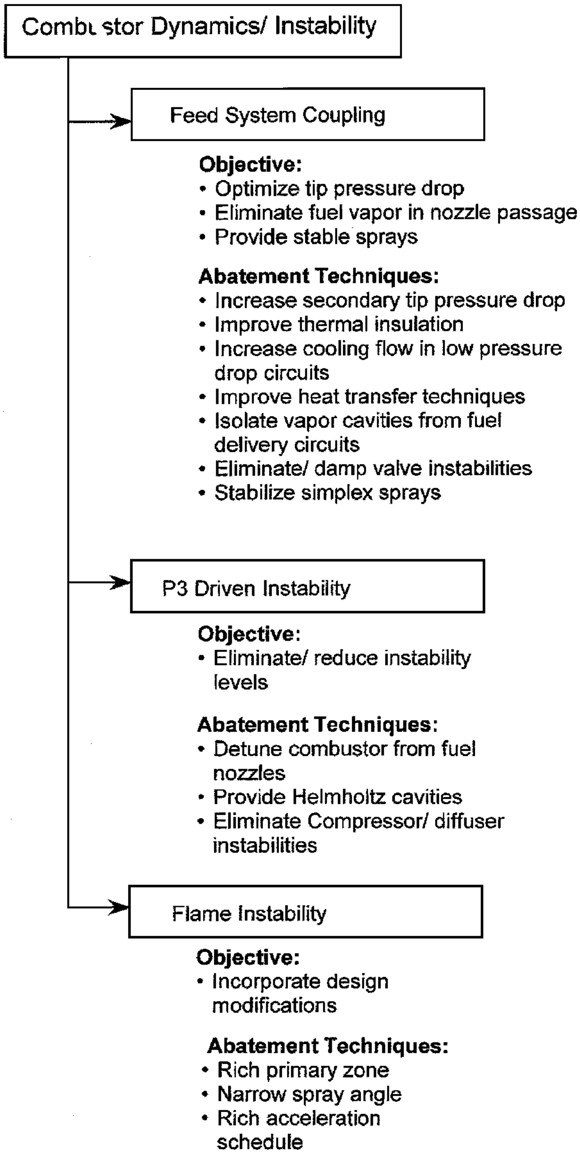
Combustion instabilities encountered in rich-dome combustors are generally observed at frequencies between 150 and 700 Hz. Typical amplitudes of combustion dynamics range from 1 to 3 psi (7 to 20 kPa) peak-to-peak during transition from start to idle and/or during transition from idle to a higher power setting. Design guidelines have been developed for designing new diffusion flame combustor concepts to eliminate potential instability problems before they appear during development phase. These guidelines have not been completely successful in eliminating the problem entirely. Once encountered, instability problems generally can be mitigated by relatively simple modifications as summarized in Table 1.

The basic concept in these fixes is to change the interaction between the fuel injection system and the combustor to eliminate coupling between the two systems.

Examples of two recent postcertification combustion instability problem encountered were on double annular combustors (DAC). In one case, the instability problem consisted of a low-frequency "growl" near ground idle condition and higher frequency instability at approximately 600–630 Hz at higher operating conditions. Subsequent analysis of test data from the engines showed two distinct frequencies associated with each of these instabilities. The first growl instability appeared at 200 Hz, followed by a second tone at 300 Hz near ground idle. Only the 200-Hz mode was audible outside the engine. A detailed evaluation of the growl instability and the potential root causes of the problem identified combustor–fuel system coupling as the most probable source. Altering the fueling strategy during the engine start transient eliminated the objectionable tone.

Two distinct frequency peaks (signals) were also observed from pressure transducers mounted on the combustor near the flame zone for the higher frequency dynamics. The two primary frequencies observed were instability at 580 Hz and a second tone at approximately 700 Hz. These acoustic modes were collectively called organ tone

Table 1 Control of combustion dynamics in conventional gas turbine combustors



due to their close proximity in frequencies to the classical organ-tone frequency. This instability occurred during operation in the high fuel flow pilot only mode. Because analytical design tools were not available in the mid-1990s when this problem was encountered, an iterative empirical approach was used to fix the instability problem. Several candidate approaches were identified and screened for easy implementation to fix the instability, including alternate fueling modes, Helmholtz resonators, fuel nozzle tertiary cavity fill/seal, and spray angle changes. The fueling mode impact on instability was selected as the prime approach. This approach involved controlling certain main burner fuel nozzles in various circumferential patterns. The rationale for this approach was to reduce the local pilot stoichiometry and to introduce circumferential nonuniformity in the main stage to reduce dynamics.

Two separate engine tests were conducted in 1997 to document the engine combustor dynamics characteristics. The first ground engine test was used to establish organ noise threshold limits as a function of combustor severity parameter and for a range of core engine speeds. Analysis of these data clearly showed the influence of an increasing pilot fuel/air ratio parameter on organ-tone amplitude. Data from the ground engine tests replicated earlier engine testing results, where two pure tones, one at 600 Hz and a second tone at 680 Hz were again observed when operating in the pilot only (20/0) fueling mode above 2000-rpm engine fan speed. A second engine test on a flight

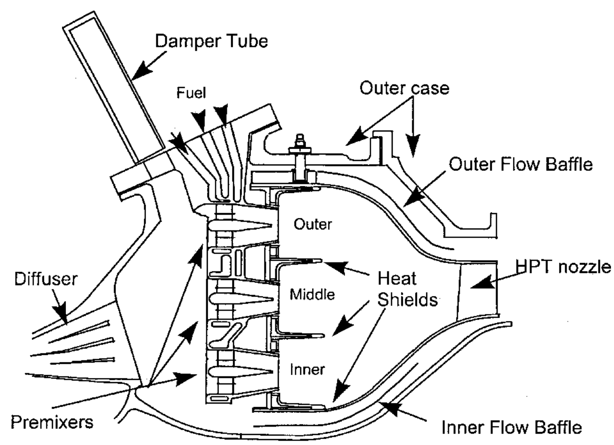


Fig. 2 LM6000 DLE combustor.

testbed was subsequently conducted to get additional data from an altitude engine environment. Data from the flight testbed engine were also used to map organ noise envelope in 20/0 fueling mode. Extensive testing of the fueling mode changes identified $20/2^2$ as the optimal configuration for the instability problem. This fueling mode incorporates two main stage fuel nozzles operating adjacent to each other at two circumferential locations in a 20 pilot and 4 main fuel nozzles combination in the operating range where the instability was observed. Subsequent engine tests validated the fueling mode change as the most practical and effective way to eliminate the dynamics problem in DAC combustors.

Dry Low-Emissions Combustion Dynamics Example

The need to reduce emissions from land-based industrial gas turbines, for example, LM1600, LM2500, and LM6000, drove the development of the dry low-emissions (DLE) lean premixed combustion system.[5,13,14] The combustion technology was systematically developed using empirical and analytical design processes and extensive component testing, including single- and two-cup and full-scale annular combustors. The rig tests were followed by final combustion system refinements on an engine test in 1994. The LM2500 and the LM1600 combustors were developed in quick succession to the LM6000 utilizing the technology developed in the process.[15]

A cross section of the LM6000 combustor is shown in Fig. 2. The combustor has three domes arranged radially to permit parallel staging of the three domes. The middle and the outer domes each consist of 30 premixers, whereas the inner dome has 15. This arrangement permits the use of standard premixer sizes in the three domes. The inner dome is at about half of the radius of the outer dome, and thus, circumferential spacing can accommodate only 15 standard premixers. To increase the air available for combustion, the combustor liners are convectively cooled using turbine cooling air.

The 75 premixers are arranged on 15 two-cup and 15 three-cup assemblies. The two-cup assemblies do not have the innermost premixer. Each cup consists of a double annular counter-rotating swirler premixer, which has two axial counter-rotating coaxial swirlers mounted with a hub separating them followed by a mixing duct.[5] The middle and inner dome premixers are identical, whereas the outer premixers are somewhat larger, such that the dome reference velocities are each nearly identical.

The fuel delivery system consists of individual fuel controls for each dome of the combustion system as described by Joshi et al.[5] (Fig. 3). Independent control of the fuel flow to each of the three domes is used to operate within the combined constraints of emissions, combustion acoustics, and demanded total fuel flow rate (shaft power). In addition, compressor air is bled from the engine at part-power operation to extend the range over which the flame temperatures can be maintained. As power is further reduced, radial and circumferential staging modes are also used to bring flame temperatures within their operating limits (Fig. 4).

Combustion dynamics can create substantial limitation to the operation of a lean premixed combustor. Three design features of the

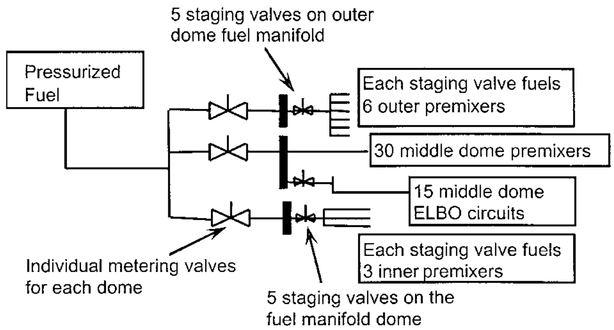


Fig. 3 Schematic of the fuel delivery system of the LM2500/6000 DLE combustion system.

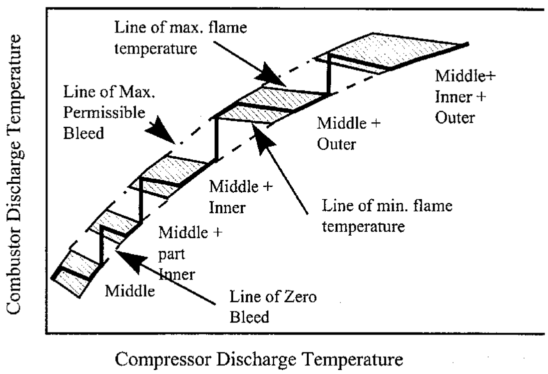


Fig. 4 Schematic of the fuel staging strategy for the LM2500/6000 DLE combustion system.

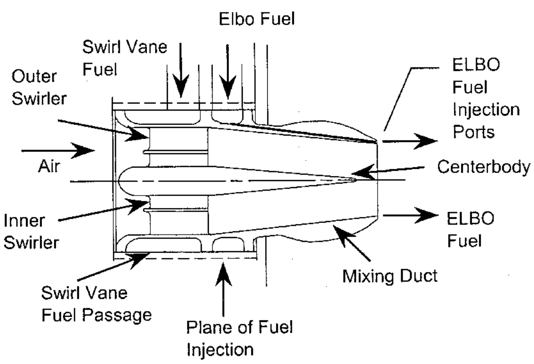


Fig. 5 LM6000 DLE premixer showing enhanced lean blow out (ELBO) fuel injection for controlling dynamics.

system are used to expand the range over which dynamics are within acceptable limits. First, a small fraction of the fuel is injected into the combustor from holes in the walls of the mixing duct (Fig. 5). This method of fuel injection has been shown in several instances to provide improved combustion dynamics performance in premixed combustion devices.

Second, a set of quarter-wave tubes is provided on the premixers, outside the engine to absorb combustion generated noise. These damper tubes, of three different lengths, are installed on the fuel nozzles on the engine as shown in Fig. 2. Each damper tube length is designed for critical operating band dynamic frequencies. The damper tubes open into the diffuser cavity and communicate with the combustor through the premixers.

Finally, the combustor dome flame temperatures are empirically scheduled to achieve low emissions and stable operation of the gas turbine engine over its entire operating range. The stable values of dome flame temperatures are affected by fuel property variation, ambient conditions, and load changes; thus unstable operation of the combustor can develop from changes in these parameters. Combustion dynamic pressures are measured continuously and monitored by the acoustics and blowout avoidance logic (ABAL) within the control system. If the monitored dynamic pressures exceed factory set limits for more than a set period, the control system takes action to alter flame temperatures based on algorithms developed in factory testing of the engines to reduce dynamic pressures to acceptable levels. If the control system is unable to effect a reduction in dynamic pressures, then it commands the gas turbine to step to idle as a precautionary measure. The ABAL logic within the control system can also detect incipient lean blowouts by comparing measured and calculated fuel flows for the operating conditions based on a cycle model calibrated for each engine. The ABAL control system increases the flame temperature in the appropriate dome when an incipient lean blowout is detected.

In summary, premixed low-emissions combustors have been designed and operated in the field for nearly a decade with combustion dynamics as a controlled but persistent issue. Further development of DLE combustion systems is limited by the risk of introducing new combustion dynamic behavior as a result of any design changes. As emissions regulations become more stringent, the evolution of flight engine combustors will likely follow the path set by the DLE combustor toward increasing levels of premixing and lower flame temperatures.[16] Thus, there is a strong need to drive the design process toward a more predictive capability of identification and mitigation of combustion dynamics phenomena in such combustors.

Combustion Acoustic Modeling

A framework for eventually developing this predictive capability is shown in Fig. 1. The basic philosophy behind this approach is the combination of analytical modeling with experimentally determined boundary and submodel behavior. The fundamentals of acoustic wave propagation are well known; thus, determination of available acoustic modes is straightforward once a temperature field is established through the use of either empirical means or by computational fluid dynamics (CFD). The remainder of the modeling problem consists of determining boundary conditions and defining the submodel behavior. In particular, the accurate modeling of the interaction of the combustion process with pressure waves is critical to the success of the overall approach.

Time-Lag Combustion Acoustic Model

The modeling of combustion acoustics in practical combustion devices is quite complex and, in general, simplifying approximations are necessary to yield computationally tractable solutions. One commonly employed approximation is the use of a single convective delay time to characterize the time-of-flight of individual fuel parcels from the point of injection to the flame front. The primary underlying assumption here is that the turbulent flame brush can be modeled as a steady contiguous thin reaction zone anchored at fixed locations within the combustion chamber. In reality, the location of the reaction sheet varies in an unsteady manner due in part to instabilities in fuel flow and airflow rates.

Even when such fluctuations are ignored, the single convective delay time approximation assumes that the flame sheet is positioned in such a manner that the time-of-flight for each fuel parcel is equivalent. The local flow velocity and turbulent flame speed determine the location of the flame sheet. Given the complexities of the flowfield aft of swirler-stabilized premixers, there can be little expectation that convective times of individual fuel parcels originating within the same premixer will be confined to a narrow range. In addition, variation between premixers, whether by design or chance, can result in further disparity in convective times.

A steady-state CFD simulation[17] of a 24 deg sector of the LM6000 DLE combustor provides an illustrative example of the variation in convective timescales. Plots of axial flow velocity, temperature, and reaction progress variable are shown in Fig. 6 for a typical high-power operating point. In each annulus, corner recirculation zones anchor the flame front. The extent of vortex breakdown and subsequent recirculation zone aft of the premixer strongly depends on the premixer swirl number and expansion ratio. The lower swirl number in the outer premixers results in a flame surface that is elongated relative to those found in the middle and inner premixers. The swirl numbers of the latter two premixers are equivalent; however,

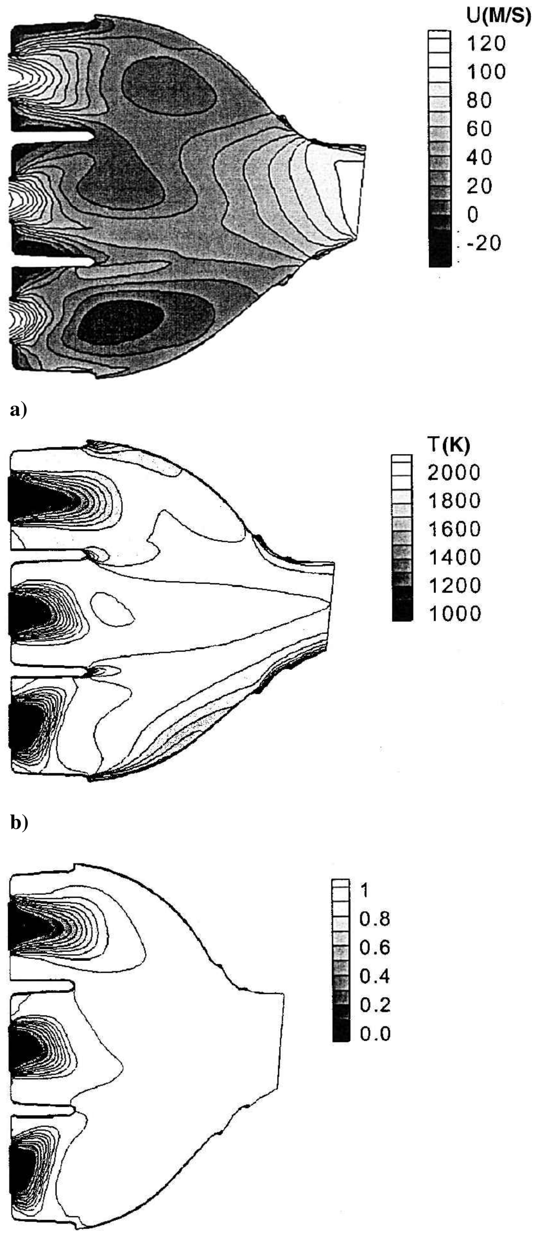


Fig. 6 Steady CFD simulation of LM6000 DLE combustor, on the plane that intersects the three-cup premixer: a) axial velocity, b) temperature, and c) reaction progress variable.

the inner premixer expansion ratio is much larger due to increased premixer spacing.

To determine computationally the location of the flame front, a threshold value of unity is chosen for the reaction progress variable $G(\boldsymbol{x}, t)$. This choice defines the flame surface as the locus of points where the local mixture is in the burned state 50% of the time. The resulting distribution of calculated convective timescales is provided in Fig. 7. Fuel/air mixing is not modeled; instead, experimentally derived profiles of velocity and mixture fraction are used as inlet boundary conditions. As such, the convective delay times represent only the time-of-flight from the premixer exit planes to the flame sheet. The time-of-flight from the injection points to the premixer exits can be determined using through-the-vane CFD simulations, but, for the purposes of this example, convective times within the combustor are sufficient to illustrate the complications of choosing a single timescale.

As seen in Fig. 7, convective times between the premixer exit and the flame front range from 0.1 to over 0.7 ms. The median, mass-weighted mean, and standard deviation are 0.40, 0.46, and 0.18 ms, respectively. For comparison proposes, the average residence time of the fuel/air mixture in the premixer is approximately 0.45 ms. Statistical differences between individual premixers are significant as median times for individual premixers range from 0.25 to 0.47 ms. The overall distribution is not well fit using either normal or log-normal distributions; log-normal distribution is shown in Fig. 7. These time lags can also be expressed as phase lags in the frequency domain. At a frequency of 500 Hz, the convective time delay range of 0.1–0.7 ms is equivalent to 18–126 deg phase lag, which covers both positive and negative Rayleigh index values. To account for the multiple convective timescales associated with the mixer, the single time-lag modeling approach is oversimplistic and may need to be expanded on to reproduce observed behavior. An approach for deriving complex premixer transfer functions from steady-state CFD simulations has recently been proposed.[18]

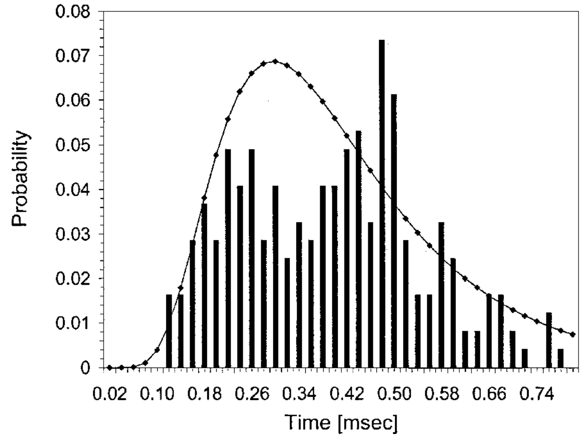


Fig. 7 Distribution of convective times from the premixer exit plane to the flame front and log-normal distribution.

Semi-empirical Combustion Acoustic Model

Rather than utilize a fully analytical description of the combustion/acoustic interaction process, judicious use of subcomponent data may provide a means for overcoming the modeling issues. By themselves, component tests, (for instance, single-cup tests of an individual fuel injector/swirler combination), cannot reproduce full engine behavior for at least three reasons. First, a full-scale annular combustor has several different natural acoustic mode shapes (and, thus, resonant frequencies) that can have significant radial and circumferential components. A single-cup test can only support a first- or second-order mode, providing only one or two resonant frequencies with which the fuel nozzle/swirler combination can interact. Second, the fuel system can potentially also play a role in affecting the phase relationship between a pressure disturbance and the resulting equivalence ratio fluctuation that reinforces the pressure wave. Third, the acoustic inflow and outflow boundary conditions are generally not well represented by a single-cup test. The choked outflow boundary of a turbine nozzle can be simulated with a restricted test combustor exit, but the inflow boundary of the final compressor stages is more difficult to simulate.

Many of these objections can be overcome by application of a computational model that encompasses the entire combustion system, including appropriate modeling of inflow and outflow boundaries, fuel system dynamics, aerodynamic pressure/equivalence ratio interactions, flame dynamics, and acoustic wave propagation. Unfortunately, not only is a full model of the dynamic system beyond current computational capabilities, many of the physical phenomena are insufficiently understood to permit first-principles modeling. In particular, the interaction of acoustic waves with the flame front, fuel flow rate, and airflow rate is complex and not well understood. Thus, the combustion/acoustic phenomena are represented by a transfer function, whose parameters are unknown, but are expected to be a function of the design details of the fuel and air injection and mixing devices. To circumvent the modeling difficulty, an experimental means of determining these interactions has been developed in a

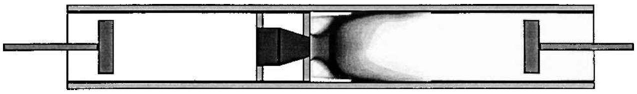


Fig. 8 TCA rig conceptual view.

relatively small-scale component test. The data obtained from this test can then be used to determine the input parameters for the full combustor simulation. The test facility is called the tunable combustor acoustic (TCA) test rig (Fig. 8) and has been applied to several General Electric Aircraft Engines industrial aero derivative combustor components. The philosophy behind the experimental design is to provide a single fuel nozzle/swirler assembly an acoustic chamber that has well-characterized boundary conditions and a continuous range of natural frequencies that covers the resonant modes typically found in full annular gas turbine combustors.

The TCA consists of an upstream chamber, a single-cup fuel nozzle/swirler assembly, and a downstream combustion chamber. Both chambers are continuously tunable using a perforated piston and actuators. Air is preheated to typical compressor discharge temperatures and passes through the upstream piston, the swirler, and downstream piston. Cooling water is introduced only near the back-pressure valve, beyond where it should have an effect on the combustion acoustics process. The acoustic response of the system is characterized by several dynamic pressure transducers located down the length of the chambers on both sides of the pistons, as well as within the fuel system feed tubes. Dynamic pressure data are collected while the combustor length is varied continuously to give a first axial acoustic mode that covers a natural frequency range consistent with engine experience. The piston is moved in both directions, thus, giving an indication of hysteresis of the system response. For relatively small acoustic levels, no hysteresis is detectable. At higher levels of response, some amount of mode locking is evident. However, these levels are beyond those sustainable in an engine without damage and are, thus, of little practical interest.

Although simple in concept, several issues make the interpretation of test results less simple than one might wish. Because of overall pressure drop limitations as well as mechanical durability issues, the flow through the pistons is not choked. However, by measuring dynamic pressures on both sides of the pistons, the complex impedance of the pistons can be determined analytically. The geometry of the combustion chamber is quite simple, only supporting axial acoustic modes of well-defined frequencies. Although this is desirable from an analytical perspective, the measured and calculated mode shapes in an annular combustor often contain a significant circumferential component. Provided that the primary acoustic coupling mechanism is through pressure-wave-induced fluctuations in equivalence ratio, lack of circumferential modes developed in the test rig will be unimportant. The typical length scale of a pressure wave is on the order of 1 m, whereas the length scale of the swirler is typically 0.1 m. From the perspective of the pressure fluctuation, the mode shape will not significantly alter the response of the fuel nozzle/swirler. However, flame dynamic response will also depend on the velocity fluctuation, which is sensitive to orientation and, thus, mode shape. This limitation cannot be easily overcome through this type of test and would require a very different approach.

A typical result from TCA test rig is shown in Fig. 9. The vertical axis is clock time, during which the downstream piston is moved from its maximum- to minimum-length position and then back to its original position. The piston velocity is constant, and thus, the axis can also be interpreted as effective combustor length. The horizontal axis is acoustic frequency, and the shaded scale indicates amplitude at the corresponding frequency. An envelope of the maximum response is shown in Fig. 9b. As is evident, the system response is strongly dependent on the combined natural resonant frequency of the combustion chamber and the response of the fuel nozzle/swirler. Because of the relative simplicity of the physical experiment, computational modeling of the test vehicle can be accomplished with confidence. The combustor/acoustic interaction is still treated as a transfer function; in this case, the experimental data are used to determine the parameters of the transfer function. Under the assumption of mode-shape/combustor response independence described earlier, this transfer function is expected to be applicable to the full-annular model of the combustor as well.

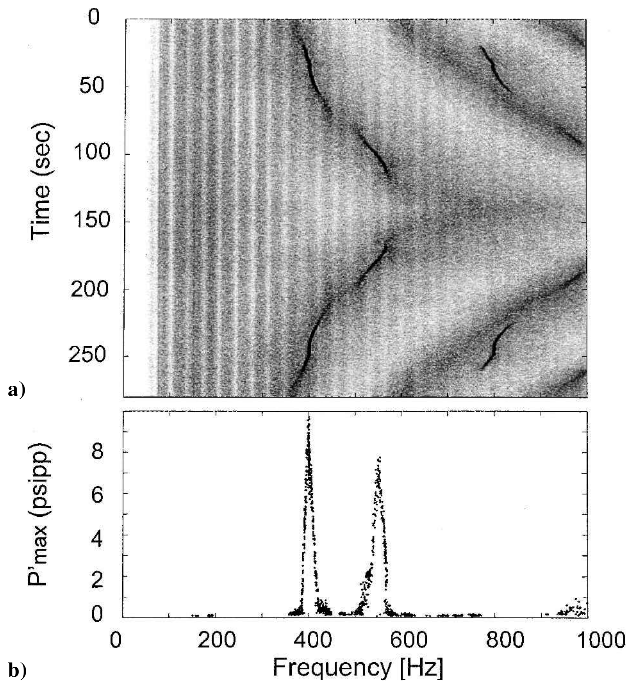


Fig. 9 Typical results from tunable combustion acoustics rig.

A significant advantage of this approach is that it permits evaluation of the impact of swirler and fuel nozzle design variables on combustion acoustics, without the expense and delay associated with construction of a full engine set of hardware and test. It also avoids the circumstance under which a design change only moves the maximum-response frequency of the fuel nozzle to a nonresonant mode of a fixed-geometry single-cup test rig. As stated earlier, a large-scale annular combustor has numerous mode shapes covering a wide range of frequencies available to it, whereas a fixed-geometry single-cup rig generally has only one or two natural acoustic frequencies. The design strategy described is still being validated and has not yet been demonstrated to completion. Given the risk to combustor and engine development schedules represented by combustion acoustics, the value of such a strategy is clear.

Large-eddy Simulation Modeling

Detailed CFD modeling of the combustion process also holds promise in the determination of combustion/pressure wave interactions. Significant progress has been made in time-dependent modeling of the combustion process through large eddy simulation (LES) for modeling combustion-generated flow instability.[19,20] As a research tool, much can be made of the fundamental insights obtained through these calculations. Significant challenges still exist in the use of these calculations as design tools.

First, most of the calculations performed are initiated at the discharge of the swirler vanes. Thus, interactions of the pressure wave with the incoming airflow have to be modeled separately. Second, the interaction of the pressure wave with the fuel flow rate (particularly for a gas-fueled device where the pressure drop is relatively low) also have to be modeled. Finally, the computational complexity of the model currently limits its application to relatively simple geometries, such as a single cup. Despite these difficulties, early results with these models are encouraging and will likely see application as submodels within a system-level acoustic model as shown in Fig. 1.

Acoustic Modeling Results

Preliminary results of combustion acoustic modeling of the LM6000 DLE combustor provide some level of confidence in the strategy described. In high-power operation, two discrete

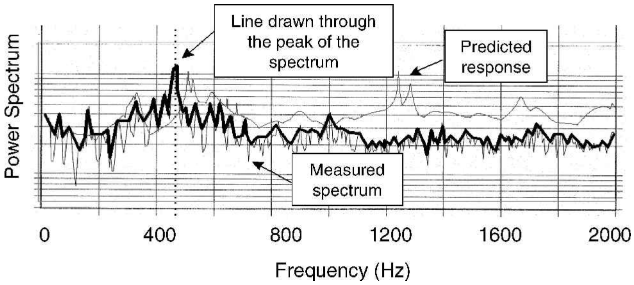
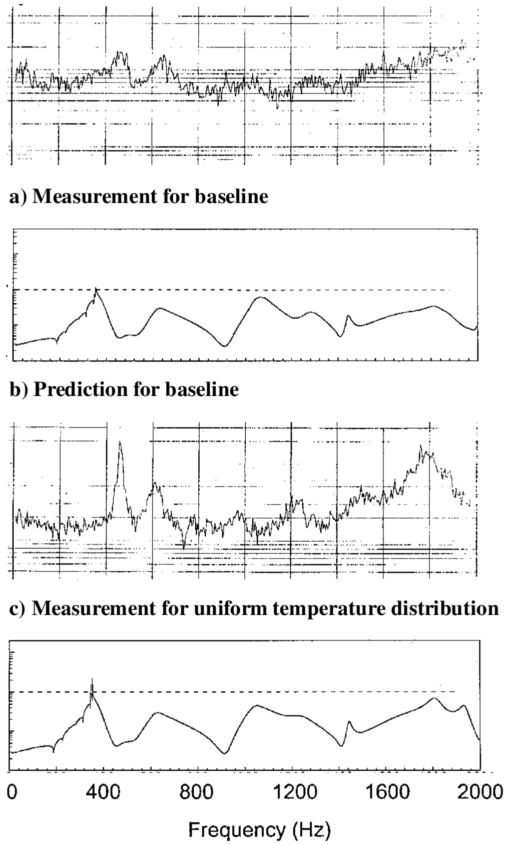


Fig. 10 Comparison of measured and predicted combustion acoustic response from LM6000 DLE.

frequencies at 450 and 600–650 Hz are typically observed. Figure 10 shows the comparison between measured and predicted dynamic response, using the single time-lag approach.[21] Two lines are shown for the measured spectra, where the thin line indicates the direct analyzer output and the bold line is frequency averaged to further smooth the plot. The predicted response is obtained by taking the maximum values of the individual response from each dome and normalizing with a reference value (peak value) from the measured spectrum plot. Characteristic convective times associated with each combustor dome are estimated based on the flame location provided by the CFD analysis. Within the frequency range of interest, the model predicts two dominant frequencies, one at 500 Hz and the other at 600 Hz. These frequencies are reasonably close to those observed from engine tests at the specified operating condition. It is also seen from Fig. 10 that the 500-Hz mode is more active compared to the 600-Hz dynamics. The predicted resonant frequency of the 500-Hz mode is approximately 50 Hz higher than that observed from engine test. This deviation may be attributed to two possible sources of error that are inherently present in the computation. First, the accuracy of the predicted flame temperature is a critical factor because of its influence on speed of sound and, therefore, contributes to errors in frequency prediction. Second, the uncertainty in estimating the location of the flame front (which is a critical input to estimate the characteristic convection time distribution) by examining the steady-state heat release contours could be a factor contributing to the discrepancy in frequency calculation. The uncertainty in calculating transport time distribution associated with the unsteady heat release will induce different phase lag into the model and, thus, predicts a different resonance frequency. Based on the current analysis, the dynamic pressures response in the vicinity of 500 Hz is mainly contributed by the plane waves from the middle and inner domes. On the other hand, the source of the 600-Hz acoustic mode appears to be the first-order circumferential mode arising in the outer ring.

The acoustic analyses of the baseline and uniform temperature distribution case were conducted to investigate the effect of radial temperature nonuniformity on combustion instability. The measured and predicted responses are shown in Figs. 11a and 11b, respectively, for baseline operation, and in Figs. 11c and 11d, respectively, for an operating condition with uniform temperature in all three domes. The measured spectra shown in Figs. 11 were based on dynamic pressure measurements from pressure sensors installed just downstream of the flame front in the DLE combustor. The predicted response is obtained by taking the maximum values of the individual responses from each of the three rings. Two distinct frequency peaks near 400 and 600 Hz were found from the analysis, similar to those observed from engine tests. It is also seen from Figs. 11 that the 400-Hz mode is more active compared to the 600-Hz dynamics for both operating conditions. In addition, the measured amplitudes of the two acoustic modes at the baseline condition showed relatively low levels. The predicted stability indices for these two peaks were less than 1 and are both categorized as acoustically inactive. In contrast, an acoustically active mode near 400 Hz with a stability index of 3 is found for the operating condition with uniform flame temperatures in all three rings. This predicted trend agrees well with test data and further demonstrates the capability of the current model to distinguish between acoustically active and inactive regimes of operation.



a) Measurement for baseline

b) Prediction for baseline

c) Measurement for uniform temperature distribution

d) Prediction for uniform temperature distribution

Fig. 11 Effect of radial temperature nonuniformity on combustion dynamics.

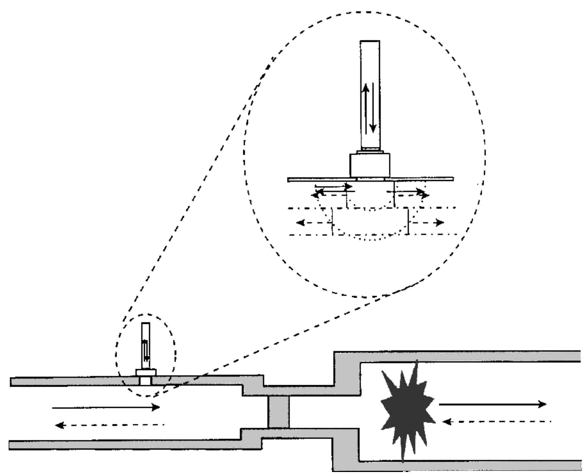


Fig. 12 Schematic of acoustic damper tube in combustor.

The methodology required to incorporate passive damping devices was a prime requirement in this modeling activity.[22,23] As mentioned in Sec. III, a set of 22 damper tubes is provided upstream of the premixers, outside the engine to absorb combustion-generated noise. Because the mean flow Mach number in the air column of these devices is very small (typically less than 0.05) and the diameter of these quarter-wave tubes is much smaller than the wave length of the resonant frequency of oscillation, the dynamic pressure and mass flow within the damper tubes can be represented by a one-dimensional analysis.

These devices are quarter-wave resonators installed in the cold section of the combustor just upstream of the premixers. The installation schematic of the damper tubes used in the formulation of this analysis is shown in Fig. 12. These devices act to detune the combustor by providing finite number of discontinuities at the locations

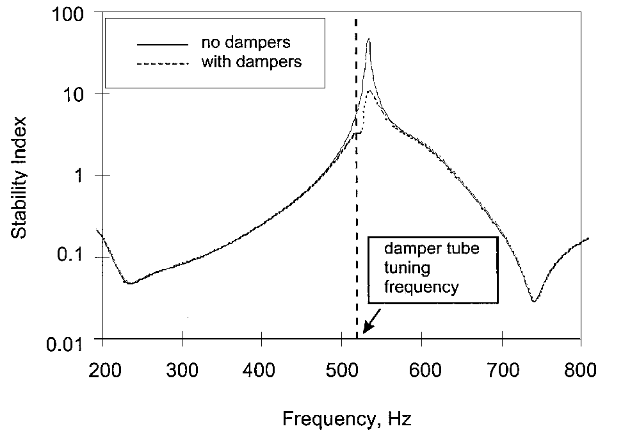


Fig. 13 Predicted impact of damper tubes on combustor acoustic response.

where they are installed. The incident and reflected acoustic waves in the diffuser cavity are significantly altered to the extent that certain discrete oscillations are attenuated and, therefore, become less destructive to the combustor. The inclusion of acoustic damping devices into the current analysis is accomplished by treating each quarter-wave tube as a monopole acoustic source characterized by an acoustic impedance. The effect of damper tubes (tuned for 510 Hz) on combustion dynamics in the pilot (middle) ring is qualitatively shown in Fig. 13. A sevenfold decrease in stability index at the tuning frequency of the damper tubes is predicted based on this analysis.

Although analytical techniques have improved markedly over the past few years, the difficulty in representing the combustion/pressure wave interaction will likely remain a barrier to full predictive capability. Thus, it is likely that a combined approach, including both experimental and high-fidelity unsteady CFD modeling, will be required to develop models of the full annular combustor response that will have utility in defining design direction.

Summary

Combustion instability in conventional diffusion flame gas turbine combustors, if encountered, can be generally eliminated with simple modifications to the design or operating parameters. The design guidelines based on empirical know-how are generally good enough to avoid unforeseen occurrence of dynamics during the engine certification phase. If encountered, simple analysis coupled with empirical guidelines and systematic testing and development process are used to find engineering solutions without adversely impacting the key combustion system design requirements.

On the other hand, controlling combustion dynamics in industrial DLE combustion systems has been a challenging tradeoff for designers. The combustion process is pushed close to the limits of lean flame stability and/or heat release rates, which leads to strongly coupled nonlinear interaction between the flame exothermicity and the acoustic behavior of the system and components. The approach for controlling dynamics in the LM engines (bleed air, fuel staging, dome flame temperatures differences, ELBO, acoustic damper tubes and ABAL control logic) has worked very well. However, to further improve on the design of lean premixed combustors, we need to make significant advances in this area.

More recent directions in propulsion engine technology are driving designs that have more in common with the lean premixed DLE combustors than with the rich-dome combustors of the past. As these designs progress toward maturity, there is a likelihood that combustion dynamics will be a limiting factor in the attainable performance of these combustors. Thus, improved predictive capability, fundamental understanding, and control technologies for combustion dynamics need to be developed. The current state of the art is represented by a combined systems approach in which empirically derived submodels are linked with a physics-based system model. In the future, we anticipate an increased role in developing LES capabilities as a tool to develop these submodels, rather than relying upon component test or engine data. In the longer term, more direct linkage of the physical coupling mechanisms between the components of the combustion system (fuel system, fuel injector, combustor cavity, and combustion/pressure wave interactions) will make it possible to describe, predict, and control accurately the physical phenomena associated with combustion dynamics.

References

[1]Lieuwen, T., "Modeling Premixed Combustion–Acoustic Wave Interactions: A Review," *Journal of Propulsion and Power*, Vol. 19, No. 5, 2003, pp. 765–781.

[2]Steele, R. C., Cowell, L. H., Cannon, S. M., and Smith, C. E., "Passive Control of Combustion Instability in Lean Premixed Combustors," American Society of Mechanical Engineers, ASME Paper 99-GT-52, June 1999.

[3]Straub, D. L., and Richards, G. A., "Effect of Axial Swirl Vane Location on Combustion Dynamics," American Society of Mechanical Engineers, ASME Paper 99-GT-109, June 1999.

[4]Paschereit, C. O., and Gutmark, E., "Passive Combustion Control for Enhanced Stability and Reduced Emissions in a Swirl-Stabilized Burner," AIAA Paper 2003-1011, Jan. 2003.

[5]Joshi, N., Epstein, M., Durlak, S., Marakovits, S., and Sabla, P., "Development of a Fuel Air Premixer for Aero-Derivative Dry Low Emissions Combustors," American Society of Mechanical Engineers, ASME Paper 94-GT-253, June 1994.

[6]Scarinci, T., and Halpin, J. L., "Industrial Trent Combustor—Combustion Noise Characteristics," American Society of Mechanical Engineers, ASME Paper 99-GT-9, June 1999.

[7]James, D., "A Solution for Noise Associated with a Series Staged DLE Combustion System," 4th International Pipeline Conf., Paper IPC2002-27342, Sept.–Oct. 2002.

[8]Schlein, B. C., Anderson, D. A., Beukenberg, M., Mohr, K. D., Leiner, H. L., and Träptau, W., "Development History and Field Experiences of the First FT8 Gas Turbine with Dry Low NO_X Combustion System," American Society of Mechanical Engineers, ASME Paper 99-GT-241, June 1999.

[9]Johnson, C. E., Neumeier, Y., Lubarsky, E., Lee, J. Y., Neumaier, M., and Zinn, B. T., "Suppression of Combustion Instabilities in a Liquid Fuel Combustor Using a Fast Adaptive Control Algorithm," AIAA Paper 2000-0476, Jan. 2000.

[10]Paschereit, C. O., Gutmark, E., and Weisenstein, W., "Structure and Control of Thermoacoustic Instabilities in a Gas-Turbine Combustor," *Combustion Science and Technology*, Vol. 138, 1998, pp. 213–232.

[11]Magill, J., Bachmann, M., and McManus, K., "Combustion Dynamics and Control in Liquid-Fueled Direct Injection Systems," AIAA Paper 2000-1022, Jan. 2000.

[12]Jones, C. M., Lee, J. G., and Santavicca, D. A., "Closed-Loop Active Control of Combustion Instabilities Using Subharmonic Secondary Fuel Injection," *Journal of Propulsion and Power*, Vol. 15, No. 2, 1999, pp. 1–7.

[13]Leonard, G., and Stegmaier, J., "Development of an Aero-Derivative Gas Turbine Dry Low Emissions Combustion System," American Society of Mechanical Engineers, ASME Paper 93-GT-288, May 1993.

[14]Joshi, N. D., Mongia, H. C., Leonard, G., Stegmaier, J. W., and Vickers, E. C., "Dry Low Emissions Combustor Development," American Society of Mechanical Engineers, ASME Paper 98-GT-310, June 1998.

[15]Patt, R., "Development and Operating Experience of DLE Combustion Systems," 12th Symposium on Industrial Applications of Gas Turbines, Paper 97-IAGT-501, Oct. 1997.

[16]Mongia, H. C., "TAPS—A 4th Generation Low Emissions Propulsion Engine Combustion System," AIAA Paper 2003-2657, July 2003.

[17]Held, T. J., Mueller, M. A., Li, S.-C., and Mongia, H. C., "A Data-Driven Model for NO_X, CO and UHC Emissions for a Dry Low Emissions Gas Turbine Combustor," AIAA Paper 2001-3425, July 2001.

[18]Flohr, P., Paschereit, C. O., and Belluci, V., "Steady CFD Analysis for Gas Turbine Burner Transfer Functions," AIAA Paper 2003-1346, Jan. 2003.

[19]Huang, Y., Hsieh, S.-Y., and Yang, V., "Numerical Modeling of Combustion Dynamics of a Lean-Premixed Swirl-Stabilized Injector," AIAA Paper 2002-1009, Jan. 2002.

[20]Stone, C., and Menon, S., "Adaptive Swirl Control of Combustion Dynamics in Gas Turbine Combustors," *Proceedings of the Twenty-Ninth Symposium (International) on Combustion*, Combustion Inst., Pittsburgh, PA, 2002, pp. 155–160.

[21]Hsiao, G. C., Pandalai, R. P., Hura, H. S., and Mongia, H. C., "Combustion Dynamic Modeling for Gas Turbine Engines," AIAA Paper 98-3380, July 1998.

[22]Hsiao, G. C., Pandalai, R. P., Hura, H. S., and Mongia, H. C., "Investigation of Combustion Dynamics in Dry Low Emission Gas Turbine Engines," AIAA Paper 98-3381, July 1998.

[23]Pandalai, R. P., and Mongia, H. C., "Combustion Instability Characteristics of Industrial Engine Dry Low Emission Combustion System," AIAA Paper 98-3379, July 1998.